Gapless topological states in bilayer graphene

M. Anđelković, L. Covaci, F. M. Peeters

CMT Group, Departement Fysica, Universiteit Antwerpen, Groenenborgerlaan 171, B-2020 Antwerpen, Belgium

20th of February, 2018.
Introduction

I Theoretical description 3

II Manipulation 8

III Is gated bilayer really gapped? Gapless states 13

IV Experimental observation and realization possibilities 15
Theoretical description

Defining the system that allow appearance of in-gap states
Graphene, monolayer and bilayer

Monolayer and AB stacked bilayer system

Brillouin zone
Graphene, monolayer and bilayer

Brillouin zone
Graphene, monolayer and bilayer

Band structure and electric field effect

Brillouin zone
Graphene, monolayer and bilayer

Brillouin zone
Graphene, monolayer and bilayer

Valley polarized topological states in bilayer graphene AB/BA nanoribbon.
Appearance of in-gap states in bilayer graphene

Kink potential configuration

- chiral topological states,
- valley polarized unidirectional motion,
- additional non chiral bands due to kink flattening,
- weakly affected by the magnetic field.

Martin et al., PRL 100, 036804 (2008)

Zarenia et al., PRB 84, 125451 (2011)
Appearance of in-gap states

Defect line

AB/BA stacking bilayer graphene produced by a pentagon-octagon defect line
a) top view, b) bottom view.

Jaskólski et al., Nanoscale 8, 6079-6084 (2016)
Appearance of in-gap states

LDOS(k) a) V=0V, with a system with a grain boundary, b), c) AB/BA bilayer graphene (corrugation) with positive and negative voltage applied to the bottom layer.

Jaskólski et al., Nanoscale 8, 6079-6084 (2016)
Appearance of in-gap states

LDOS(k) a) V=0V, with a system with a grain boundary, b), c) AB/BA bilayer graphene (corrugation) with positive and negative voltage applied to the bottom layer.

LDOS(k) AB/BA bilayer graphene induced by a octagon-pentagon grain boundary with a) positive and b) negative voltage applied to the bottom layer.

Jaskólski et al., Nanoscale 8, 6079-6084 (2016)
Appearance of in-gap states

Domain wall

Tilt boundary (stacking change) + corrugation (delamination)

Vaezi et al., PRX 3, 021918 (2013)
Zhang et al., PNAS 110, 10546–10551 (2013)
Pelc et al., PRB 92, 085433 (2015)
Lane et al., PRB 97, 045301 (2018)
W Jaskólski et al., 2D Mater. 5 025006 (2018)
Manipulation
Manipulation

Understanding the motion to be able to design the functionality
Delamination in bilayer graphene

\[ H = -\sum_{l} \sum_{i,j} \gamma_0 e^{i2\pi \phi_{ij}/\phi_0} c_{l,i}^\dagger c_{l,j} - \sum_{i,j} \left\{ \left[ (\theta(y_i) + (\theta(y_i - W))] \gamma_1 c_{1,i}^\dagger c_{2,j} + H.C. \right \} + \sum_i V_{\pm} c_i^\dagger c_i \]

\( \gamma_0 = 3.1 \text{eV} \)
\( \gamma_1 = 0.39 \text{eV} \)

\[ V_{\pm} = \Delta(y_i) + U(y_i) + \delta(y_i) \]
Delamination in bilayer graphene

\[ H = - \sum_l \sum_{i,j} \gamma_0 e^{i2\pi \phi_{ij}/\phi_0} c^\dagger_{l,i} c_{l,j} - \sum_{i,j} \left\{ [\left( \theta(y_i) + (\theta(y_i - W)\right)] \gamma_1 c^\dagger_{1,i} c_{2,j} + H.C. \right\} + \sum_i V_{\pm} c^\dagger_i c_i \]

\[ \gamma_0 = 3.1 \text{eV} \]
\[ \gamma_1 = 0.39 \text{eV} \]

\[ V_{\pm} = \Delta(y_i) + U(y_i) + \delta(y_i) \]

\[ U = 0 \text{eV} \]
\[ \Delta = 0.2 \text{eV} \]

\[ \delta = 0.2 \text{eV} \]
\[ \delta = 0.3 \text{eV} \]
\[ \delta = 0.4 \text{eV} \]

Lane et al., PRB 97, 045301 (2018)
Delamination in bilayer graphene

\[ \delta = 0.2eV \]

\[ \delta = 0.3eV \]

\[ \delta = 0.4eV \]

\[ U = 0eV \]

\[ \Delta = 0.2eV \]

Lane et al., PRB 97, 045301 (2018)
Delamination in bilayer graphene

- localized along the edges,
- monolayer bouncing bands are distributed along delamination.

Lane et al., PRB 97, 045301 (2018)
Delamination in magnetic field

\[ r_0 \sim l_B = \sqrt{\frac{\hbar}{eB}} < \frac{W}{2} \]

\[ \vec{F}_{\text{L}} = e\vec{v} \times \vec{B} \]

Lane et al., PRB 97, 045301 (2018)
Delamination in magnetic field

\[ r_0 \sim l_B = \sqrt{\frac{\hbar}{eB}} < \frac{W}{2} \]

\[ \mathbf{F}_L = e\mathbf{v} \times \mathbf{B} \]

Lane et al., PRB 97, 045301 (2018)
Delamination in magnetic field

Lane et al., PRB 97, 045301 (2018)

\[ r_0 \sim l_B = \sqrt{\frac{\hbar}{eB}} < \frac{W}{2} \]

\[ \overrightarrow{F_L} = e\vec{v} \times \vec{B} \]
Delamination in magnetic field

\[ r_0 \sim l_B = \sqrt{\hbar/eB} < W/2 \]

\[ \mathbf{F}_L = e\mathbf{v} \times \mathbf{B} \]

Lane et al., PRB 97, 045301 (2018)
Layer polarization

- layer degree of freedom beside the valley and sublattice,
- tuned by doping and modified by electric field.

Layer dependent LDOS(k). Red and blue show localization in top and bottom layer respectively.

W Jaskólski et al., 2D Mater. 5 025006 (2018)
Gapless states in gated bilayer. Is the gated bilayer really gapped?

Domain walls, stacking solitons

Obtaining different stacking through domain wall, strain soliton

STEM images and simulation of AB-BA domain boundary, shear + tensile strain soliton.

Koshino, PRB 11, 115409 (2013)

Alden et al., PNAS 110 (28), 11256-11260 (2013)
Change of stacking

Dark-field TEM of a large bilayer graphene flake.

Lin et al., Nano Lett. 13 (7), 3262–3268 (2013)
Change of stacking

Dark-field TEM of a large bilayer graphene flake.

Lin et al., Nano Lett. 13 (7), 3262–3268 (2013)
Change of stacking

Dark-field TEM of a large bilayer graphene flake.

AFM topography map of bilayer graphene on SiO$_2$/Si + graphene monolayer bottom right.

Near-field infrared nanoscopy of the same sample.

Lin et al., Nano Lett. 13 (7), 3262–3268 (2013)

Ju et al., Nature 520 (7549), 650-655 (2015)
Experimental observation and realization possibilities
Topological transport at a domain wall

AB/BA domain walls in exfoliated bilayer graphene

Topological transport at a domain wall

AB/BA domain walls in exfoliated bilayer graphene

Gating a bilayer graphene flake, sample with and without a domain wall. Applied perpendicular electric field, appearance of boundary states.

- conductance on the order of $\frac{2e^2}{h}$, smaller due to gate resistance, shorter channels up to $\frac{4e^2}{h}$
- MFP up to 400 nm,
- limitation random appearance.

Imaging of topological states

STM image of the domain wall states. Dependence on the Fermi energy.

Imaging the domain wall states in the magnetic field.

Yin et al., Nat. Comm. 7, 11760 (2016)
Manipulation of domain walls

- move, erase, and split the domain walls with an AFM tip,
- most are stable at room temperature.

Manipulation of domain walls

Manipulation of domain walls

Manipulation of domain walls

Manipulation of domain walls

Near-field infrared nanoscopy images of treated samples of bilayer and trilayer graphene

Manipulation of domain walls

Anisotropy in creation

Creation of different shapes

Manipulation of domain walls

Anisotropy in creation

Creation of different shapes

Manipulation of domain walls

Anisotropy in creation

Creation of different shapes

Manipulation of domain walls

Anisotropy in creation

Creation of different shapes

Double gating

- lithography limitations,
- MFP up to 200 nm,
- resistance close to $\frac{h}{4e^2}$ larger,
- valley valve and beam splitter, 4 gate structure.

Li et al., Nat. Nano. 11, 1060–1065 (2016)
Jing et al., arXiv (2018)
Conclusion

I Possibility to define ballistic transport channels could lead to **low power dissipation devices**.

II Prospective applications in fields of **valleytronics** and very recently suggested **layertronics**.

III Approach is **applicable to different materials and structures**.

Is there a **possibility to control spin** in similar manner in TMDC-s, with strong spin-orbit coupling?
Electronic transport in 2D Materials

CMT
Condensed Matter Theory
cmt.uantwerpen.be
Pybinding is a scientific Python package for numerical tight-binding calculations in solid state physics. If you're just browsing, the **Tutorial** section is a good place to start. It gives a good overview of the most important features with lots of code examples.

As a very quick example, the following code creates a triangular quantum dot of bilayer graphene and then applies a custom asymmetric strain function:

```python
import pybinding as pb
from pybinding.repository import graphene

def asymmetric_strain(c):
    @pb.site_position_modifer
def displacement(x, y, z):
        ux = -c/2 * x**2 + c/3 * x + 0.1
        uy = -c/2 * x**2 + c/3 * y
        return x + ux, y + uy, z
    return displacement

model = pb.Model(
    graphene.bilayer(),
    pb.regular_polygon(num_sides=3, radius=1.1),
    asymmetric_strain(c=0.42)
)
model.plot()
```